

## **Abstract**

*Title of Thesis:* Characterization of Time and Temperature Dependent Mechanical Properties of Advanced Polymers Using Bragg Grating Sensors

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The use of polymers in electronic packaging is continuously increasing, due to their relative ease of manufacturability and low cost. Since polymers exhibit time and temperature dependent behavior, their visco-elastic properties must be characterized in order to predict the behavior of package assemblies during manufacturing and operation. The testing methods for visco-elastic properties have been developed for many decades and some of them are routinely practiced using commercially available equipment. However, some of the methods are too time-consuming or complex to be implemented routinely by non-experts; the specimen preparation and the testing conditions are very critical to reliable and repeatable measurements.

A novel method is proposed to characterize the visco-elastic behavior rapidly but accurately. The method utilizes a polymer cured around a fiber Bragg grating (FBG) to form a complete specimen. An instantaneous mechanical load is applied to the specimen while equilibrated at a temperature within an environmental chamber, and the Bragg wavelength (BW) shift is documented as a function of time. The load applies an instantaneous, constant stress to the polymer substrate, which in turn applies a strain to the fiber. The relationship between the BW shift and the creep compliance can be derived directly from the theoretical behavior of the FBG. The creep compliance can then be obtained from the BW shift data

at each temperature. By undergoing a de-convolution process the creep compliance can be converted into the time dependent relaxation modulus. This process can then be repeated for a range of temperatures, which results in relaxation modulus data as well as the initial modulus for each temperature.

**Characterization of Time and Temperature Dependent Mechanical Properties of Advanced  
Polymers Using Bragg Grating Sensors**

By

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## Table of Contents

i. List of Figures.....	iv
ii. Chapter 1: Introduction .....	1
iii. Chapter 2: Theoretical Background.....	4
iv. Chapter 3: Proposed Method .....	11
v. Chapter 4: Implementation .....	17
vi. Chapter 6: Conclusions and Future Work .....	32
vii. References .....	34

## List of Figures

Figure 1: Schematic of Visco-elastic Measurements.....	4
Figure 2: Illustration of the generalized Maxwell model [7] .....	7
Figure 3: Schematic diagram of an FBG sensor embedded in a cylindrical substrate .....	11
Figure 4: Schematic of Specimen and Loading Condition .....	11
Figure 5: Total BW Shifts for 10% Compliance Increase and given Initial Strain and Configuration ....	13
Figure 6: Required Weights for Given Initial Strains .....	15
Figure 7: Calibration of Fibers .....	17
Figure 8: Schematic of Specimen Preparation .....	18
Figure 9: Specimens after Curing .....	18
Figure 10: Schematic of Visco-Elastic Testing .....	19
Figure 11: Schematic of Visco-elastic Testing.....	20
Figure 12: Specimen for Visco-elastic Testing .....	20
Figure 13: Preliminary BW Shift during Visco-elastic Testing .....	22
Figure 14: Preliminary Time-dependent Compliance.....	23
Figure 15: Preliminary Initial Modulus at Given Temperatures .....	24
Figure 16: BW Shift during Visco-elastic Testing .....	25

Figure 17: Time-Dependent Compliance Data..... 26

Figure 18: Comparison of Initial Modulus Data ..... 26

Figure 19: Time-Dependent Relaxation Modulus Data in real time (above) and log time (below)..... 27

Figure 20: Shifted Relaxation Master Curve..... 28

Figure 21: WLF Function and Shift Factors ..... 29

Figure 22: Prony Series and Averaged Master Curve ..... 30

## Chapter 1: Introduction

Polymer use in electronic packaging is a critical issue in the semiconductor industry. Polymers are used in all aspects of a semiconductor package, including (1) the packaging of the integrated circuit chips, (2) the interconnections for signal and power transmission, and (3) the encapsulations for protecting the chips and interconnections from the environment. Polymer choice greatly affects the reliability and performance of an electronic system, therefore advanced materials considerations can allow more demanding packaging schemes to be possible [1].

Various testing methods for characterization of polymers have been developed and are used commonly. However, all the techniques focus on one or two properties of the material and different techniques are employed when different properties are to be measured. The glass transition temperature ( $T_g$ ) is commonly measured using a Dynamic Mechanical Analyzer (DMA) [ASTM D7028 - 07e1]. A small deformation is applied to a sample held in an environmental chamber, and the resulting force is measured. Once the deformation is complete, the temperature can be scanned to the next value. The force required to deform the sample is used to calculate the storage modulus. The glass transition temperature is seen as a large drop in the storage modulus, and often cannot be defined as a discrete temperature, but rather as a range. Time and temperature dependent modulus properties are commonly measured using either static or dynamic loading. Static loading can be applied by a variety of available testing machines, to either perform creep testing (constant stress applied to specimen) or stress relaxation (constant strain applied) at a variety of temperatures. The resulting strain or stress values (respectively) can be used to calculate the compliance or relaxation modulus. However, compared to metals, polymers have a much smaller modulus, so non-contact extensometers are preferred. Dynamic testing is often performed using DMA, which can measure the time-dependent shear modulus when working in the transient step strain mode and applying a tension loading to the specimen.

DMA can be performed in four different modes; tension, compression, bending, or torsion. Tension mode is generally applied for film type polymers. There can be problems related to the grip when using a thick, rigid specimen (such as those used in electronic packages), either through slipping, or having alignment issues. Compression mode is generally applied to elastomers or rubbers, and it requires that the surface must be absolutely flat. Very high strain (on the order of 10%) is generally applied to negate these localized effects; however, when using rigid samples, the DMA cannot exert the required pressure to achieve these high strains. Either bending mode or torsion mode is typically used for the polymers of interest to packaging engineers. The bending mode measures bending (flexural) modulus, which in general does not match Young's modulus, since it depends on the structure of the polymer. There can also be a certain amount of discrepancy between specimens with different thicknesses. Torsion mode is used to measure the shear modulus, so an accurate Poisson's ratio is required to determine Young's Modulus. The main advantage of DMA is that it is a well-established technique with reliable accuracy, providing proper implementation of the testing. However, there is no way to directly get Young's modulus for a thick, rigid polymer using conventional methods.

The specimen preparation and the testing conditions can be very critical for the results to be reliable and repeatable measurements by non-experts. Design engineers cannot rely on the properties provided by polymer manufacturers since the testing conditions and other testing details associated with the properties are not always available. In addition, very limited material property data are available for new polymeric materials. Even in the case of well-known polymeric materials, the published property data can often vary by an order of magnitude. The significant variations in the published data are caused by inherent differences and the complexity involved in specimen preparation and testing procedures. The amount of available polymers continues to increase, while product cycle time decreases. This introduces a need for efficient, accurate measurement of properties of new polymers.

The accurate determination of key properties can enhance the performance, reliability, and design optimization process of electronic systems. The glass transition temperature ( $T_g$ ) and time and temperature dependent modulus of a polymer are vitally important to the success of the electronic product as a whole. Trade-offs must be considered in all cases, which is why the precise measurement of these properties is critical.

This study implements a new technique, which will allow for accurate measurement of all the properties mentioned, using the same sample and testing conditions. It implements a fiber Bragg grating (FBG) sensor embedded in a polymer substrate. The concept of using fiber Bragg gratings to document material properties embedded in a polymer substrate has been explored [2]. This technique advances to use the cured specimen of the property evolution techniques [3] to determine the time and temperature dependent modulus of the polymer, as well as identifying the glass transition region.

## Chapter 2: Theoretical Background

Time and temperature dependent modulus (visco-elastic) measurement is commonly done using either creep or stress relaxation testing. Creep testing involves applying a constant stress instantaneously to the specimen and measuring strains as a function of time while maintaining the stress. Stress relaxation imparts an instantaneous, constant strain, while the resulting stress is recorded. These tests are repeated over a desired range of temperatures to yield a full set of time and temperature dependent data.

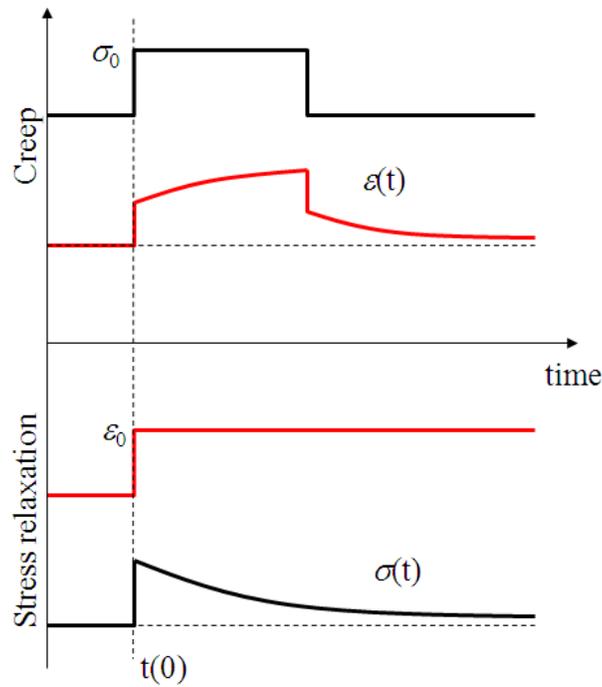


Figure 1: Schematic of Visco-elastic Measurements

Depending on the test used, either the creep compliance,  $C(t)$ , or the relaxation modulus,  $E(t)$  can be found as shown

$$\frac{\epsilon(t)}{\sigma_0} = C(t) , \quad \frac{\sigma(t)}{\epsilon_0} = E(t) \quad (1)$$

Both properties describe the material behavior completely and accurately, but since the master curve of relaxation modulus is more widely used in commercial finite element analysis software such ANSYS, it is preferable to have the master curve of relaxation modulus rather than creep compliance. However, for a given experimental set up, creep compliance may be easier to implement accurately, and therefore a conversion method is needed. Creep compliance and relaxation modulus are both manifestations of the same molecular mechanisms and can therefore be related by the convolution integral [4, 5]

$$\int_0^t C(t-\tau)E(\tau)d\tau = t \quad (2)$$

If the integral domain is divided into  $n$  sufficiently small intervals,  $E(\tau)$  will not vary much over each interval and can be approximated by an average value of  $(E_i + E_{i-1})/2$  where  $E_i$  stands for  $E(t_i)$ . The same approximation is made for the compliance and equation (2) becomes

$$\sum_{i=1}^n \frac{1}{4} (E_i + E_{i-1})(C_{n,i} + C_{n,i-1})(t_i - t_{i-1}) = t_n$$

where  $C_{n,i}$  stands for  $C(t_n - t_i)$ . Separating the last term in the above equation will yield

$$E_n = -E_{n-1} + \frac{4t_n - \sum_{i=1}^{n-1} (E_i + E_{i-1})(C_{n,i} + C_{n,i-1})(t_i - t_{i-1})}{(C_0 + C_{n,n-1})(t_n - t_{n-1})} \quad (3)$$

where  $C_0$  is the short time limit of the creep compliance. Equation (3) is a straightforward recursion relation which starts with  $E_0 = 1/C_0$  and calculates each new value from previously obtained results.

This operation can be performed (using MATLAB) for each set of creep compliance data to yield a new data set of relaxation modulus for each temperature.

The temperature has a dramatic influence on the rate of visco-elastic response of polymers, which is why visco-elastic properties must be measured over a wide range. With the assumption of thermorheologically simple, the relation between time and temperature can be described by simple models. In this case, the effect of lowering the temperature is simply to shift the relaxation modulus curve (plotted against log time) to the left without change in shape. It is also called the time-temperature superposition principle. A time-temperature shift factor  $a_T(T)$  can be defined as the horizontal shift that must be applied in log time to the relaxation curve  $E(t)$ , measured at an arbitrary temperature  $T$  to obtain the curve at some reference temperature  $T_{ref}$ . Or it can be expressed as

$$\log(a_T) = \log(t(T)) - \log(t(T_{ref})) \quad (4)$$

The WLF function is widely used to describe how the shift factor depends on the temperature and it can be expressed as [6]

$$\log(a_T) = \frac{-C_1(T - T_{ref})}{C_2 + (T - T_{ref})} \quad (5)$$

where  $C_1$  and  $C_2$  are material constants whose values depend on the material and choice of reference temperature  $T_{ref}$ .

A series of relaxation data taken over a range of temperatures can be converted to a single “master curve” via this horizontal shifting. Firstly, a particular curve is chosen as reference. Then the other curves are shifted horizontally to obtain a single curve spanning a wide range of log time [7]. Curves obtained at temperature lower than the reference temperature appear at longer times, so they will

have to be shifted left; this is a positive shift as we have defined the shift factor in Eq. (4). Each curve produces its own value of  $a_T$ , so that  $a_T$  becomes a tabulated function of temperature. With the concept of master curve, the visco-elastic behavior of a polymer at an arbitrary time scale or temperature is uniquely defined.

For modeling purposes, the obtained master curve of relaxation modulus can be then fitted by the Prony series. The theoretical base of the Prony series lies in the generalized Maxwell model (or Wiechert model), which is shown in Figure 2.

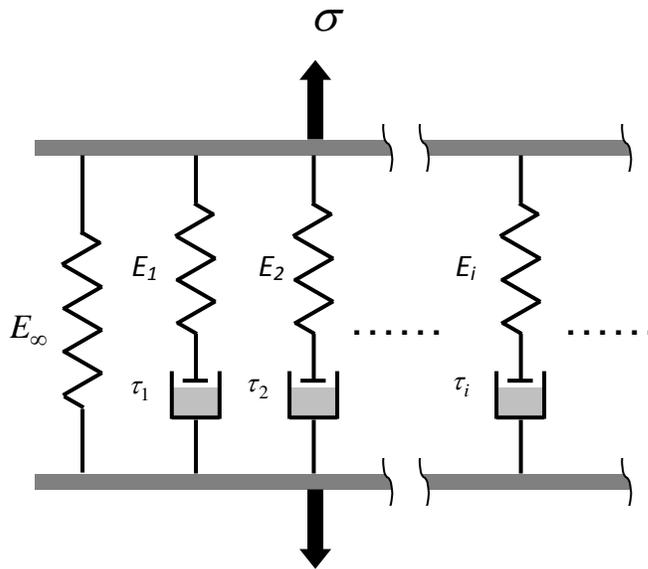


Figure 2: Illustration of the generalized Maxwell model [7]

As illustrated in the figure, the polymer is modeled by a parallel connection of an isolated spring ( $E_\infty$ ) and many spring-dashpot (Maxwell) elements. Each spring-dashpot has different relaxation time which is defined as

$$\tau_i = \frac{\eta_i}{E_i} \quad (6)$$

where  $\eta_i$  is the viscosity of the  $i^{th}$  element and  $E_i$  is the modulus of the  $i^{th}$  element. Many spring-dashpot elements are used because a real polymer does not relax with a single relaxation time. It has been found that simpler and shorter segments relax much more quickly than the longer ones, leading to a distribution of relaxation times. The generalized Maxwell-Voight model illustrated in Fig. 2 can have as many spring-dashpot elements as are needed to approximate the distribution satisfactorily.

The behavior of the  $i^{th}$  element can be described by the differential equation

$$\dot{\varepsilon}_i = \frac{\dot{\sigma}_i}{E_i} + \frac{\sigma_i}{\eta_i} \quad (7)$$

With a constant strain of  $\varepsilon_0$  imposed, the solution of Equation (7) will be

$$\sigma_i(t) = E_i \varepsilon_0 \exp\left(-\frac{t}{\tau_i}\right) \quad (8)$$

Adding the stress in every element together will yield the total stress

$$\sigma(t) = E_\infty \varepsilon_0 + \sum_{i=1}^n E_i \varepsilon_0 \exp\left(-\frac{t}{\tau_i}\right) \quad (9)$$

where  $n$  is the number of spring-dashpot elements. Then the relaxation modulus  $E(t)$  can be determined to be

$$E(t) = \frac{\sigma(t)}{\varepsilon_0} = E_\infty + \sum_{i=1}^n E_i \exp\left(-\frac{t}{\tau_i}\right) \quad (10)$$

Equation (10) is the called Prony series representation of relaxation modulus. A pair of  $E_i$  and  $\tau_i$  are referred to be a Prony pair. With Equation(10), the obtained master curve of relaxation modulus

can be fitted using nonlinear regression scheme. Then the results can be imported directly into FEM codes for the modeling of the visco-elastic behavior.

Fiber Bragg gratings are widely used as strain sensors. The Bragg wavelength is defined as

$$\lambda_B = 2n_{eff}\Lambda \quad (11)$$

where  $\lambda_B$  is the Bragg wavelength,  $\Lambda$  is the grating pitch, and  $n_{eff}$  is the effective refractive index. External disturbances from changes in either the temperature or strain on the fiber will cause a shift in the Bragg wavelength (BW). In a uni-axial loading condition of

$$\varepsilon_2 = -\nu\varepsilon_1 \quad (12)$$

where  $\varepsilon_2$  is the transverse strain,  $\varepsilon_1$  is the axial strain, and  $\nu$  is the Poisson's ratio of the fiber, at constant temperature; the change in BW can be shown [8-11] to be linearly proportional to the axial strain on the fiber,

$$\Delta\lambda_B = \lambda_B(1 - P_k)\varepsilon_1 \quad (13)$$

where  $P_k$  is the effective strain-optic constant and defined as

$$P_k = -\frac{n^2}{2} [P_{12} - \nu(P_{11} + P_{12})] \quad (14)$$

Therefore, the BW shift can be used throughout a variety of measurements to determine the stress state of the fiber, and consequently, the stress state of the matrix in which it is embedded. Wang et al. [12] have developed a method to document the evolution of the curing properties of a polymer by implementing two configurations of polymer substrate. An FBG is immersed in the polymer of interest, which is then cured while the BW shift is continuously documented. The two configurations allow for

two unique sets of BW data, and can be used to solve for the evolution of the modulus and the chemical shrinkage. This technique could be further extended to use the specimens in the cured state, as this paper details. A combination of the two processes would allow for all material properties of interest to packaging engineers to be determined using just two specimens. This would result in a streamlined procedure which could be easily performed by technicians.

### Chapter 3: Proposed Method

The proposed method utilizes cylindrical specimens [12]. The FBG is of radius  $a$ , immersed in a polymer of radius  $b$ . A schematic is shown in Figure 3.

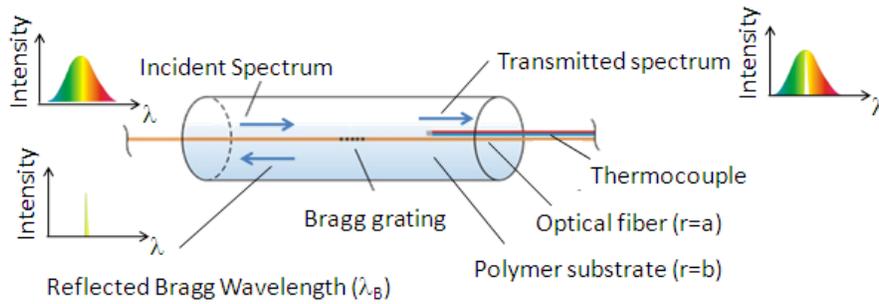


Figure 3: Schematic diagram of an FBG sensor embedded in a cylindrical substrate

The temperature and time dependent modulus requires only one specimen. Once cured, the specimen should be subjected to an instantaneous uni-axial load, as shown schematically in Figure 4.

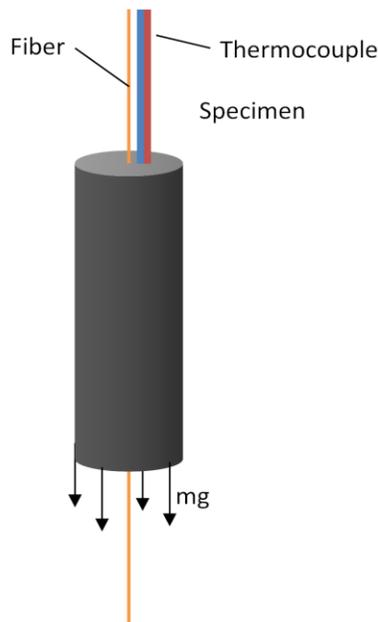


Figure 4: Schematic of Specimen and Loading Condition

The force equilibrium equation can then be expressed as

$$E_f \cdot \varepsilon(t) \cdot \pi \cdot a^2 + 1/C(t) \cdot \varepsilon(t) \cdot \pi \cdot (\beta^2 a^2 - a^2) = F \quad (15)$$

where  $E_f$  is the modulus of the fiber,  $\varepsilon(t)$  is the time dependent axial strain on the specimen,  $C(t)$  is the time dependent compliance of the polymer,  $\beta = \frac{b}{a}$ , and  $F$  is the force exerted by the weight (mg).

Similarly to the notation shown previously, if the BW shift is denoted as  $\Delta\lambda_B$ , the axial strain is

$$\varepsilon(t) = \frac{\Delta\lambda_B(t)}{\lambda_B(1-P_k)} \quad (16)$$

which can then be used to solve directly for the time dependent compliance of the polymer

$$C(t) = \left( \frac{\lambda_B(1-P_k)F}{\pi(\beta^2-1)a^2\Delta\lambda_B(t)} - \frac{E_f}{\beta^2-1} \right)^{-1} \quad (17)$$

In industry applications, the relaxation modulus is more commonly used for implementation in models. The compliance can be converted into relaxation modulus data by following the de-convolution procedure, as was outlined previously in equations (2)-(3). This procedure is then repeated for a range of temperatures, to obtain a full spectrum of the relaxation modulus behavior. The weight used at each temperature should be controlled to provide less than 0.6% strain to the specimen, in order to remain in the linear visco-elastic range.

To determine the appropriate  $\beta$  to be used for the testing, a trade-off between practical consideration of the force that needs to be applied, approximate modulus values, and the required strain rate needed for meaningful data should be considered. In addition, Wang's procedure [12] discusses a

guideline for meaningful curing data, which should be followed if the specimens are to be used for all types of testing. The presumed range of modulus for the material should be considered to determine which configuration sizes should be constructed. In general, a preliminary test should be completed initially to determine the range of modulus values and compliance amounts at different temperatures. The data from this initial test can then be used to construct testing guidelines for a more accurate test that is better suited to the material. A range of simulations to determine the appropriate strain rate, given the presumed modulus, can be used to determine the weight needed to be applied.

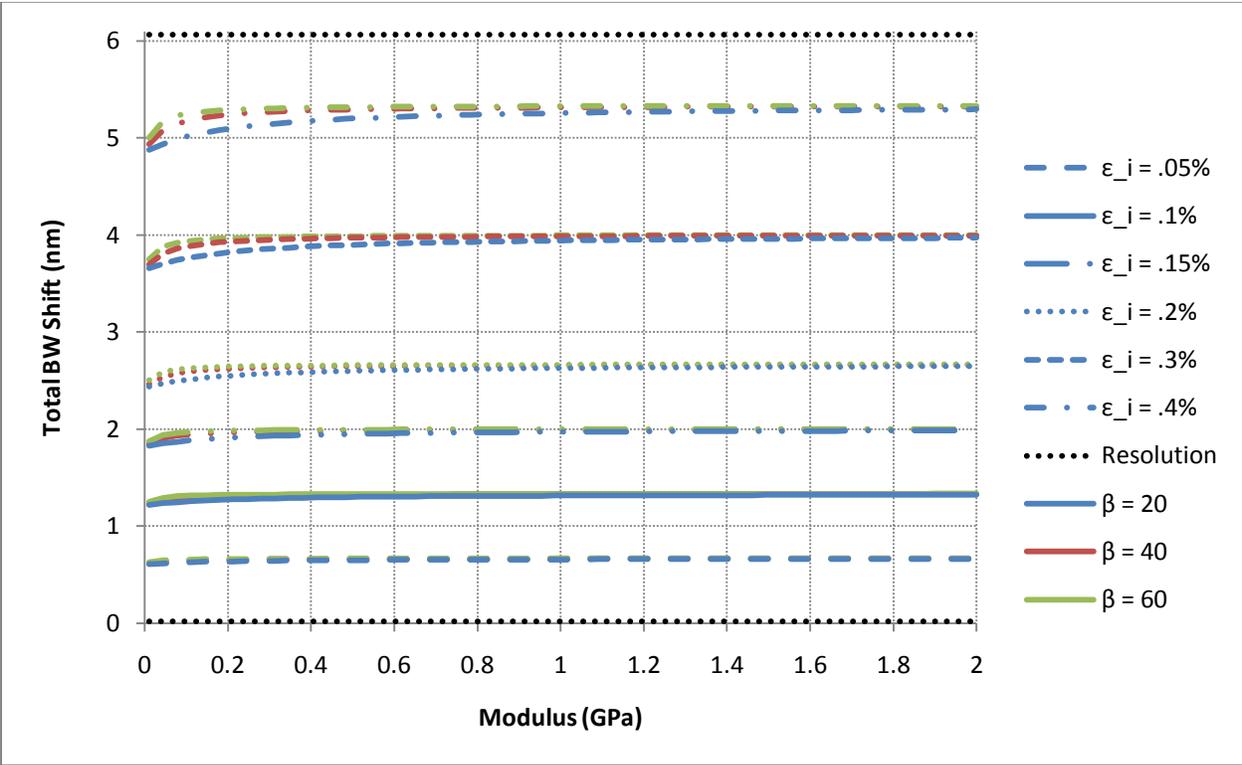


Figure 5: Total BW Shifts for 10% Compliance Increase and given Initial Strain and Configuration

A presumed compliance increase of 10% is very conservative, and can be considered a lower bound. This prediction would be better suited to temperatures outside of the glass transition region. For temperatures within the glass transition region, the material will have orders of magnitude greater

compliance, which is acceptable as long as the total BW shift does not exceed to maximum allowable strain of 0.5%. If a large compliance increase is expected (particularly around the glass transition region), lower strain rates allow for a more conservative response.

Once the desired specimen configuration and strain rates are chosen, the appropriate weights can be determined. The practical limitations of the set-up used in this study prevent weights larger than a few kilograms to be used.

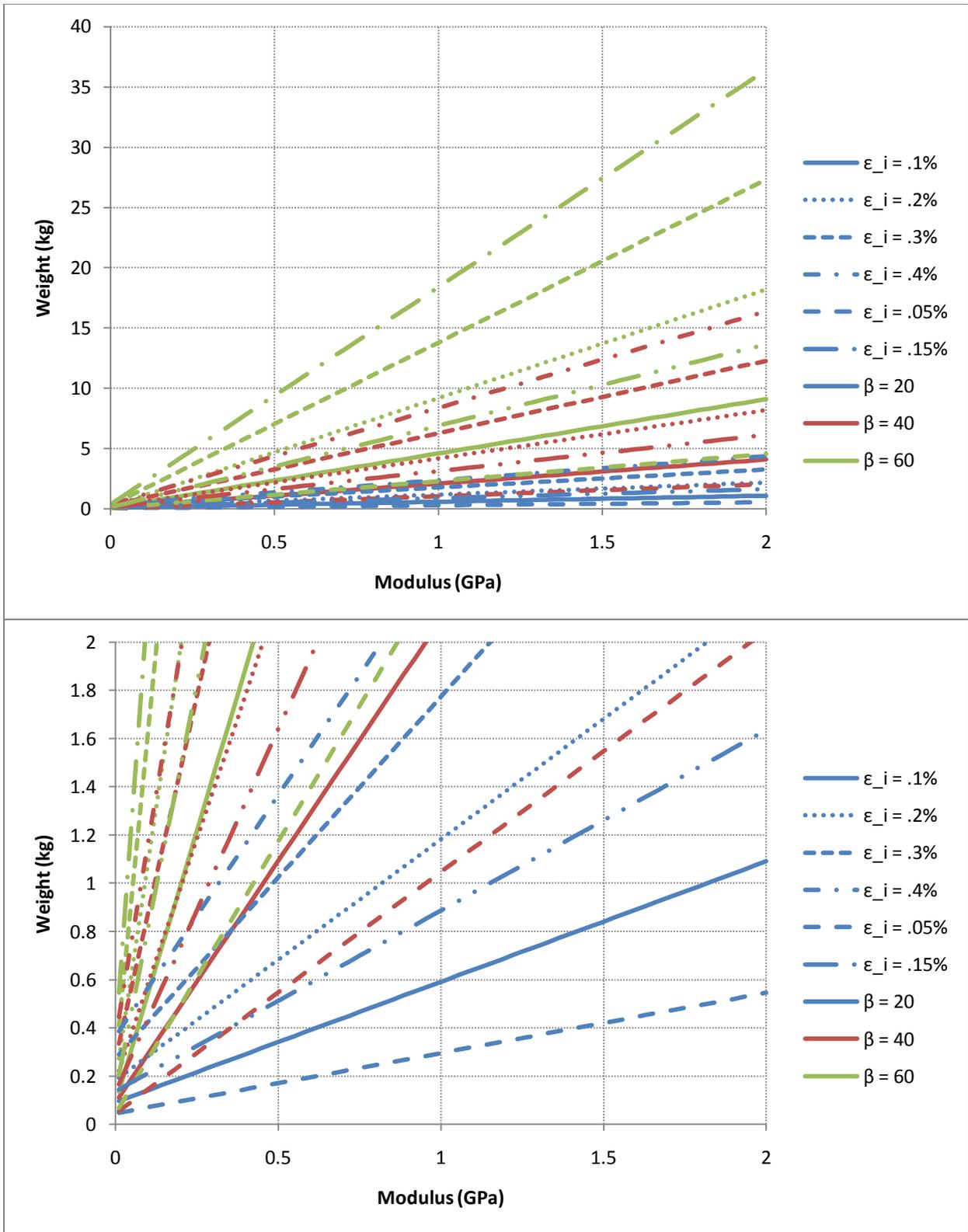


Figure 6: Required Weights for Given Initial Strains

For the preliminary testing, the initial values of weights (and therefore initial strains) should be rather low, so to avoid any possibility of reaching the critical strain on the fiber. Once preliminary testing is complete, and a more comprehensive testing plan can be executed, higher strain rates (and weights) can be considered. The results from the optimized tests can then be used to determine the time dependent compliance, which can then be used to ultimately complete the relaxation modulus master curve and Prony series function, as described earlier.

## Chapter 4: Implementation

The proposed method is implemented for a typical polymer adhesive available for commercial use, Tra-Con Tra-Bond F114. As mentioned in the proposed method, the fabrication of the specimens will follow Yong's procedure [12], but will be summarized here. The fiber Bragg gratings must be subjected to a calibration procedure, prior to being embedded in the epoxy. The fibers should be subjected to a linear temperature ramp while in an environmental chamber, to determine the intrinsic BW shift, which will then be subtracted from the measured BW shift, to determine the deformation-induced BW shift. The calibration of the two fibers used is shown in Figure 7.

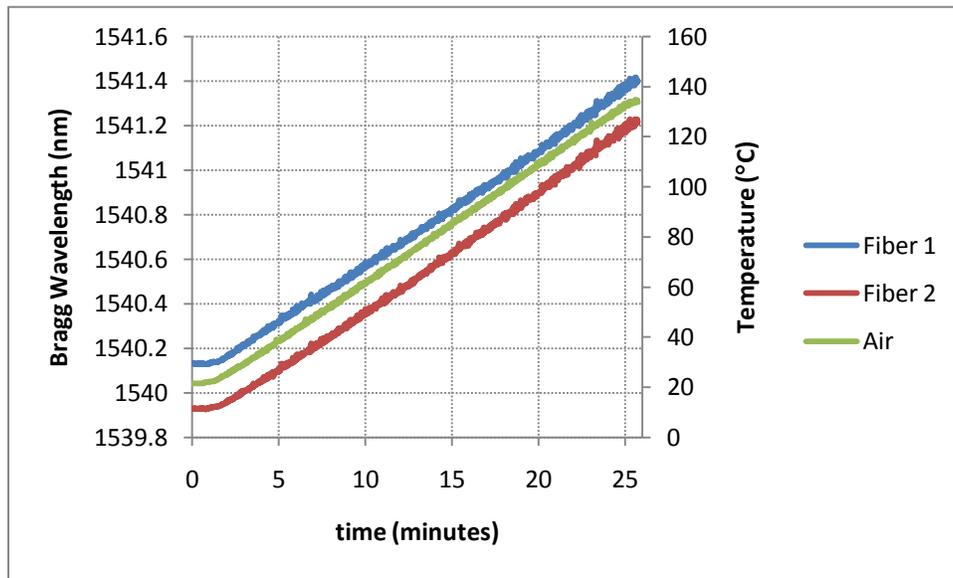
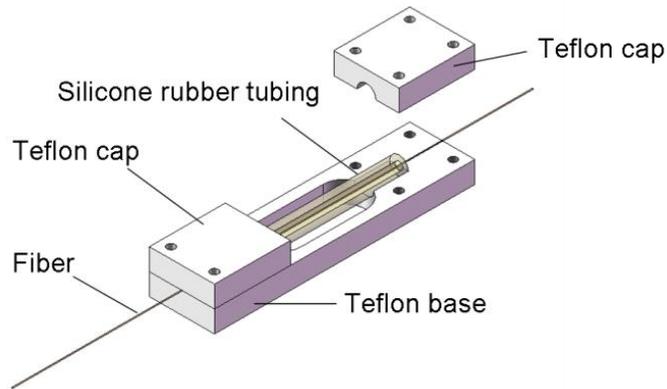


Figure 7: Calibration of Fibers

As mentioned previously, the epoxy must be cured symmetrically around the fiber. To minimize constraints on the specimen during curing, a silicone rubber and Teflon mold is used. Depending on the material used, as discussed in [12], different pairs of configurations should be considered. For the initial visco-elastic measurement,  $\beta_2 \approx 20$  was chosen, as the smaller configuration size helps to ensure

uniform curing of the specimen, and allows for flexibility in the application of the visco-elastic testing, as discussed previously.



*Figure 8: Schematic of Specimen Preparation*

The epoxy is then cured according to the manufacturer's suggestions; in the case of F114 [13], at room temperature for 24 hours. Once fully cured, the silicone rubber tubing can be removed, and the specimen is complete. An example of the sizes of the specimens is shown in Figure 9; the rounded tip is a result of the mold configuration. The specimens can then be used in two testing configurations; one for the visco-elastic properties, and one for the measurement of the CTE and  $T_g$ .



*Figure 9: Specimens after Curing*

The time and temperature modulus testing set up follows the schematic shown in Figure 10. The specimen is placed in an environmental chamber, and uses a sophisticated stage within the environmental chamber to apply the instantaneous load, as shown in Figure 11.

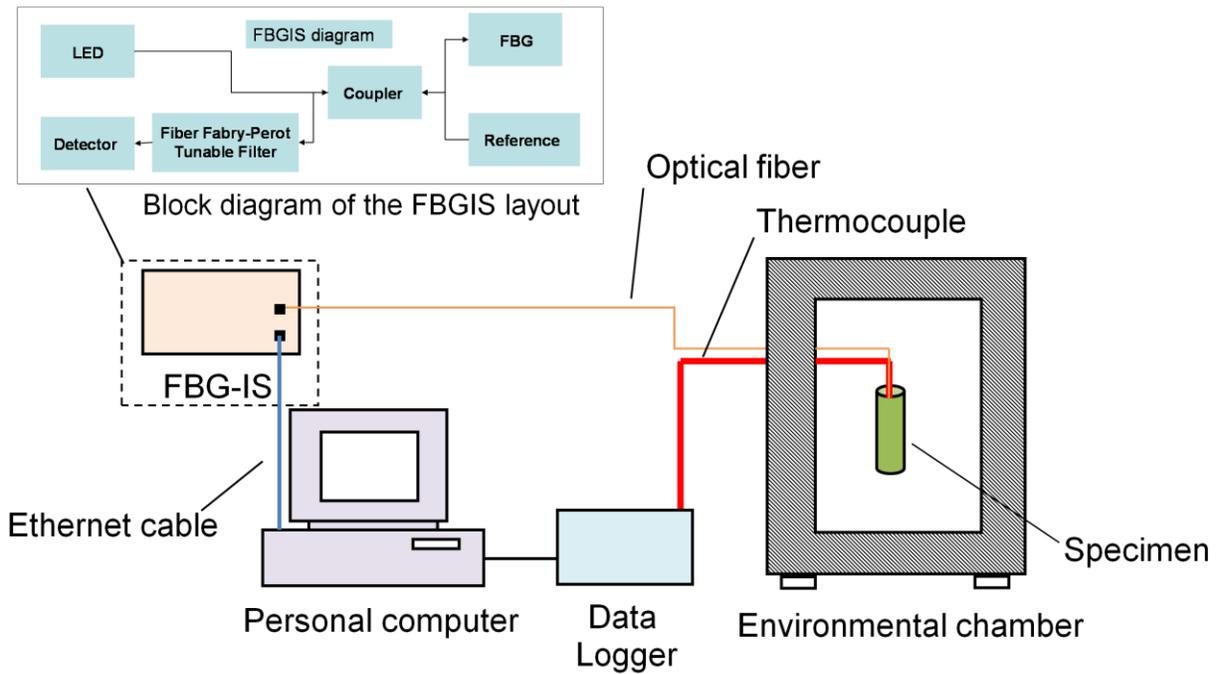
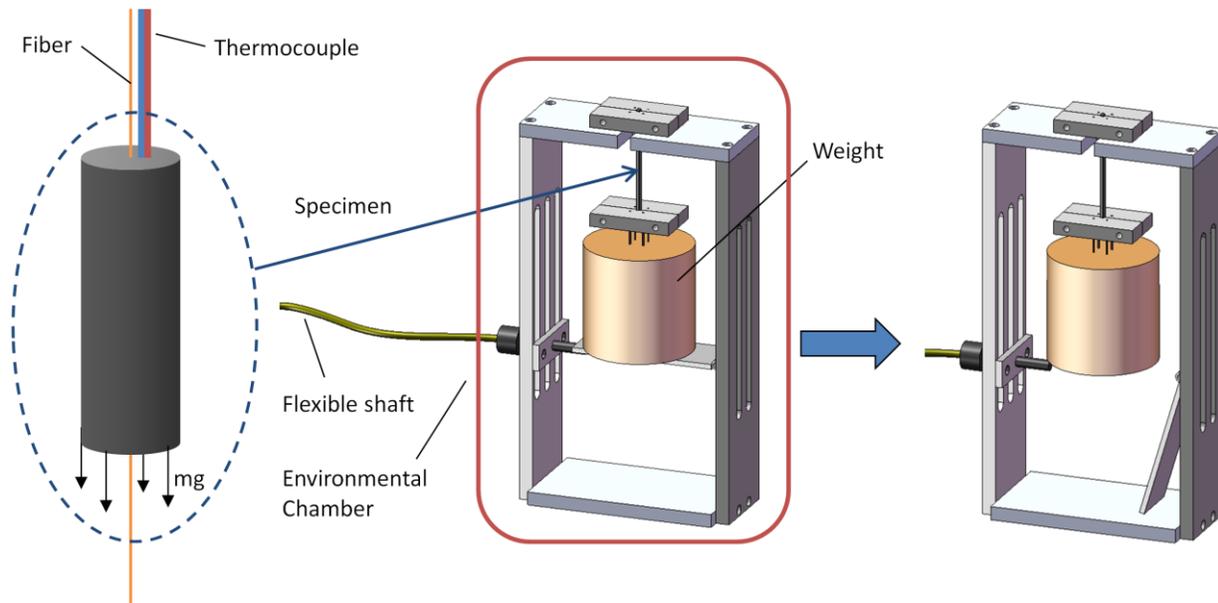
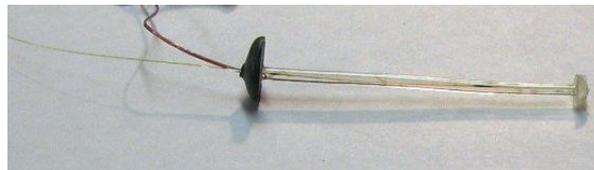


Figure 10: Schematic of Visco-Elastic Testing



*Figure 11: Schematic of Visco-elastic Testing*

The weight is clamped to the bottom end of the specimen, which is supported on the aluminum stage. The flexible shaft extends outside of the environmental chamber, and allows the hinge to be removed under the weight, instantaneously applying a load to the specimen. To ensure that the specimen does not slip through the clamps when the weight is applied, a bead of high strength epoxy is applied to the top surface, as shown in Figure 12.



*Figure 12: Specimen for Visco-elastic Testing*

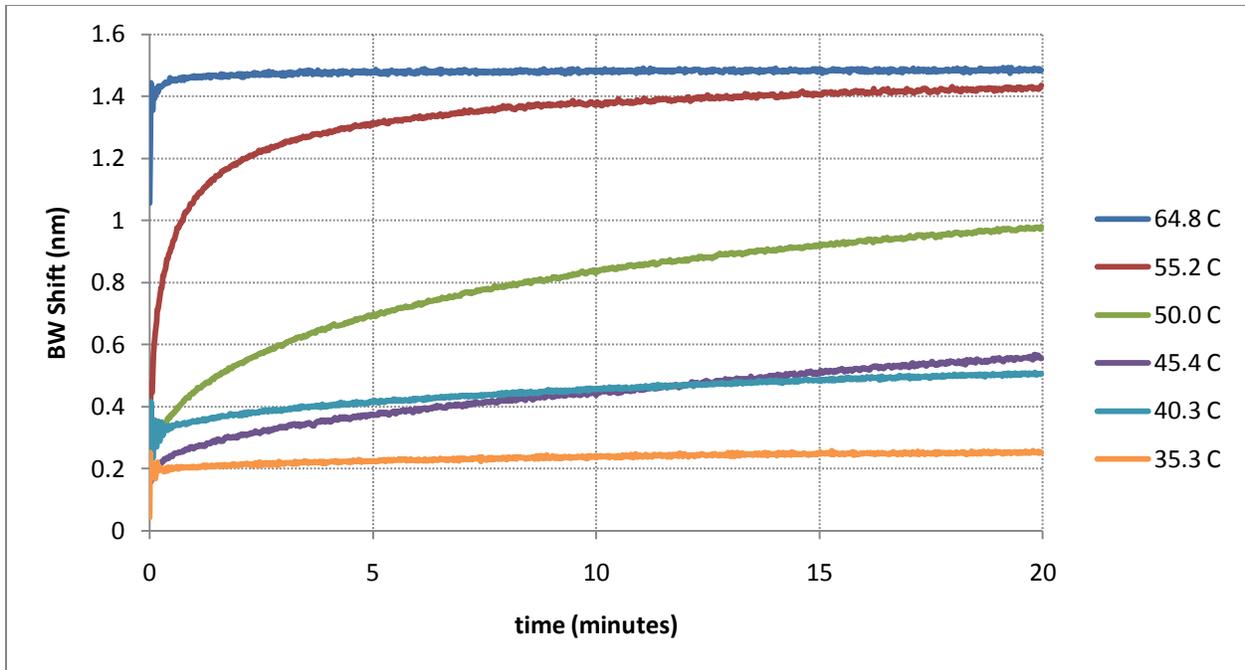
Once the desired temperature within the environmental chamber, the internal specimen temperature, and the BW of the specimen are stabilized, the load can be applied. The weight is held for

at least 20 minutes, to observe the compliance behavior. The load is then removed by replacing the hinge under the specimen. In practice, the highest temperature in the range desired is used to begin, and subsequent temperatures are lower. This is to prevent over-stretching of the specimen, from both the applied load and thermal expansion. The process is then repeated for the desired range of temperatures, at temperature increments small enough to capture the compliance behavior. For the case of F114, the following temperature range and weights were used as a preliminary test, using the configuration of  $\beta = 19$ , to determine the range of modulus at different temperatures.

Temperature	Weight
64.8	118 g
55.2	118 g
50.0	118 g
45.4	118 g
40.3	220.3 g
35.3	220.3 g

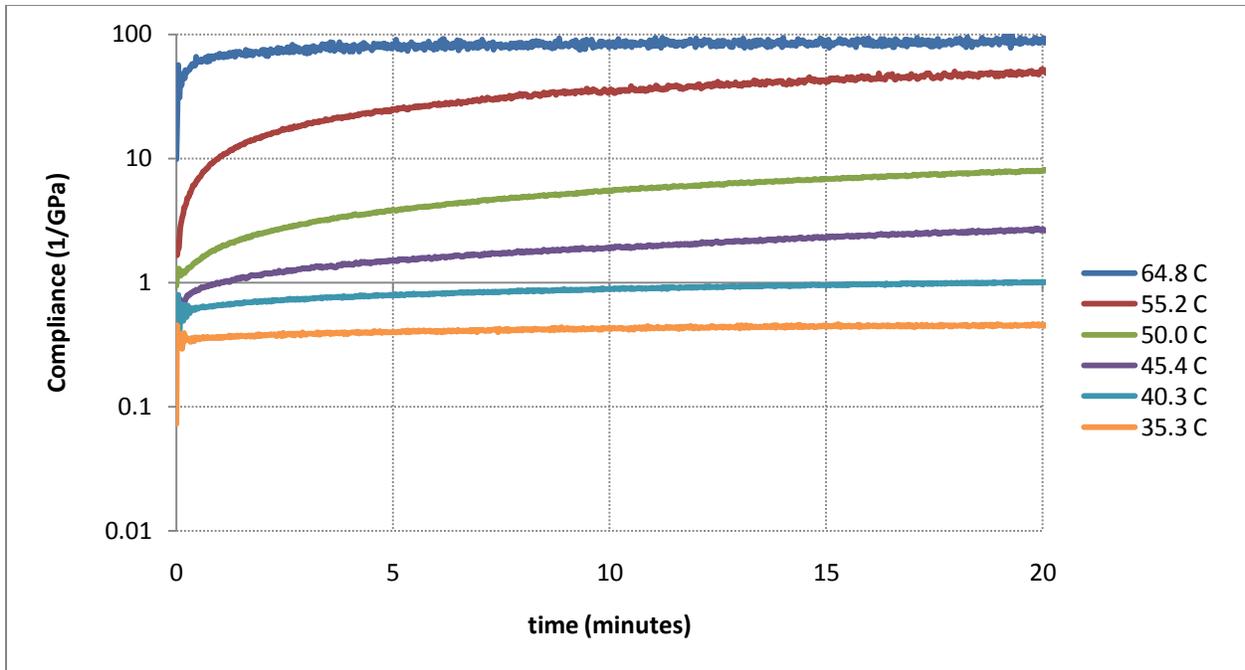
*Table 1: Temperatures and Weights for Preliminary Visco-elastic Testing*

The resulting BW shifts for each temperature are shown in Figure 13. The oscillations at the beginning of the measurement are due to the initial force of the weight being dropped, and do not affect the overall measurement.



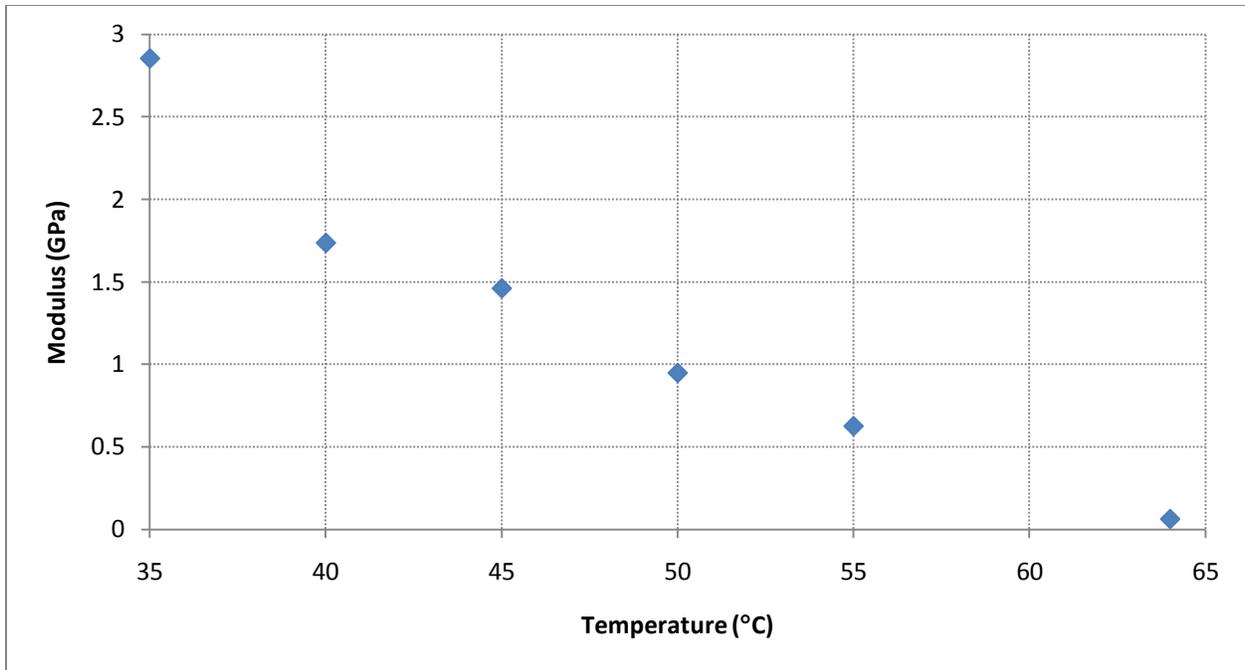
*Figure 13: Preliminary BW Shift during Visco-elastic Testing*

Using Equation(17), the BW shift can be easily used to calculate the time-dependent compliance behavior, as shown in Figure 14.



*Figure 14: Preliminary Time-dependent Compliance*

As discussed in the theoretical background, the time dependent compliance data can be transferred to relaxation modulus data by undergoing a de-convolution procedure, outlined in equations (2) - (3). After completing this process for each set of data, an initial relaxation modulus can be found for each temperature. This allows a more structured testing plan to be created, to ensure that the strain rates used will be sufficient for meaningful data.



*Figure 15: Preliminary Initial Modulus at Given Temperatures*

This preliminary initial modulus data can then be used with the sensitivity study discussed previously to determine the optimal visco-elastic testing conditions, as shown in

<b>Temp (°C)</b>	<b>E (GPa)</b>	<b><math>\beta</math></b>	<b>desired strain</b>	<b>desired weight (kg)</b>	<b>obtainable weight (kg)</b>
65 and above	0.060467	20	.2%	0.2369	0.31013
55	0.623829	20	.1%	0.3709	0.41243
50	0.946603	20	.1%	0.5152	0.53013
45	1.459522	20	.1%	0.7451	0.8797
40	1.735293	20	.1%	0.8713	0.8797
35 and below	2.853974	20	.1%	1.3762	1.07183

*Table 2: Visco-elastic Testing Plan*

This testing plan was then executed, as mentioned previously, beginning with the highest temperatures. The resulting BW shifts are shown in Figure 16, and as described previously can be easily turned into time-dependent compliance data, shown in Figure 17.

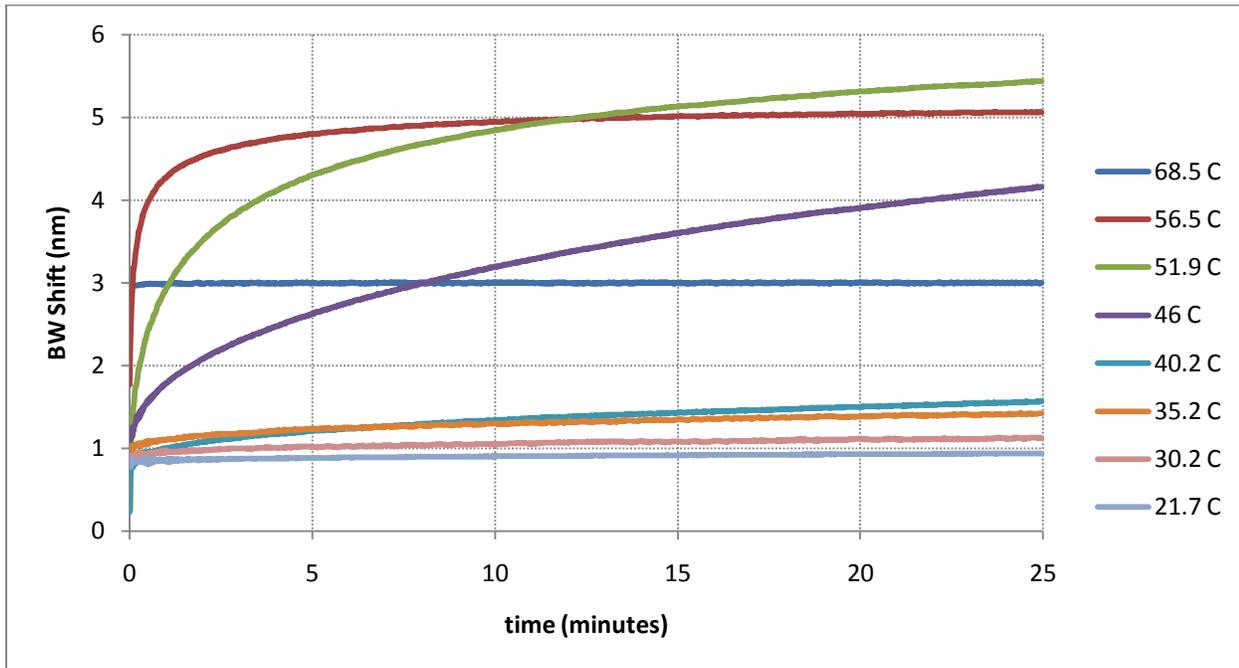


Figure 16: BW Shift during Visco-elastic Testing

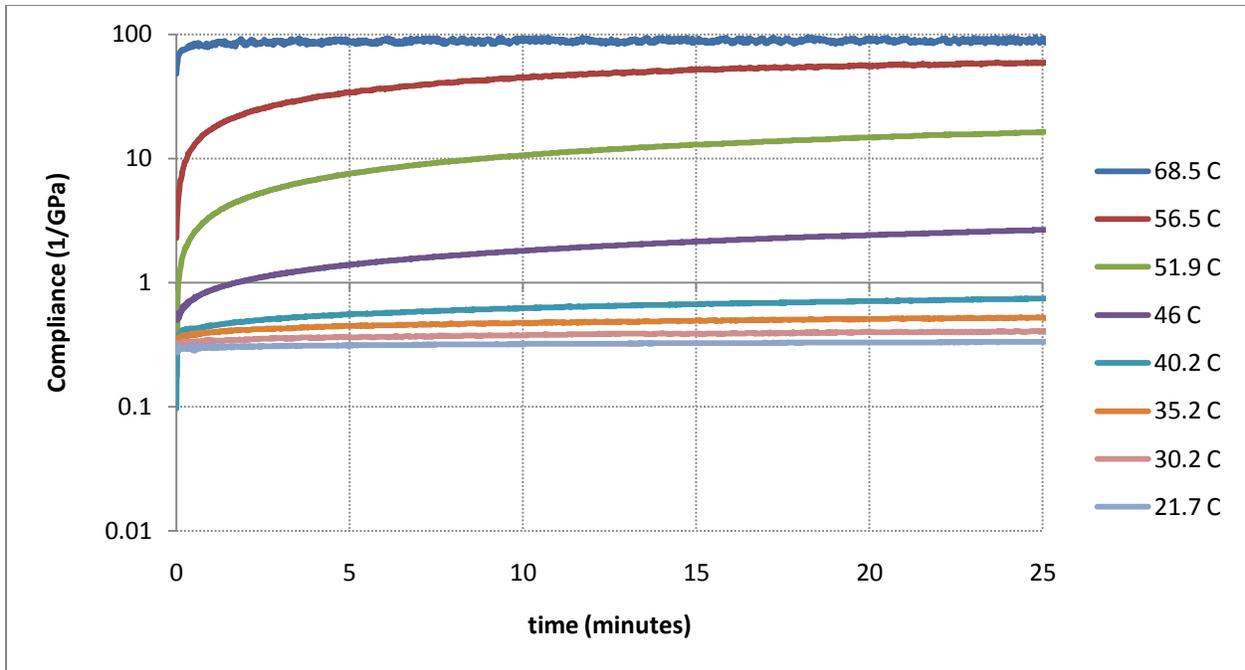


Figure 17: Time-Dependent Compliance Data

The de-convolution procedure is then repeated for the new set of data, and yields a relaxation modulus values at each temperature. These values can be used to find the initial modulus, shown in Figure 18.

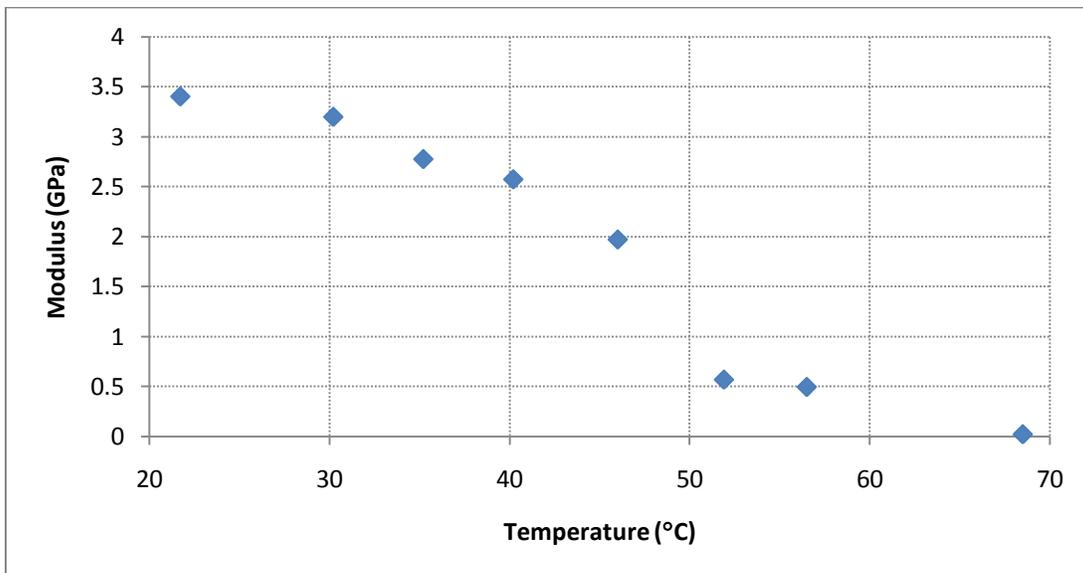


Figure 18: Comparison of Initial Modulus Data

From the data, it is clear that the glass transition region is between 45 and 55 °C, due to the rapid changing in material behavior. The time dependent relaxation modulus data is shown in Figure 19.

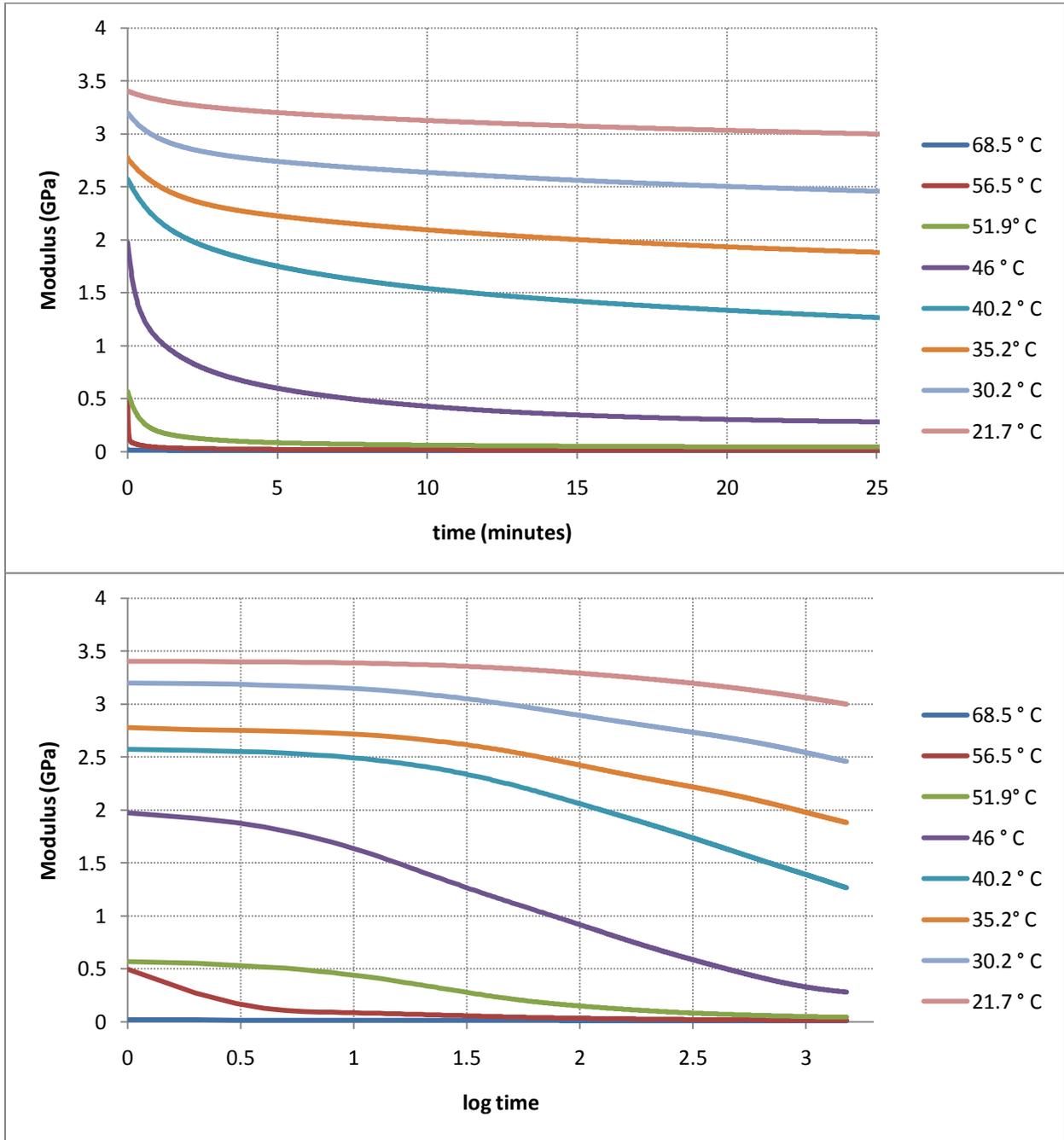


Figure 19: Time-Dependent Relaxation Modulus Data in real time (above) and log time (below)

Following the assumption of thermorheologically simple, the relaxation modulus curves can be shifted along the log time axis, to form a complete master curve of relaxation data, as shown in Figure 20.

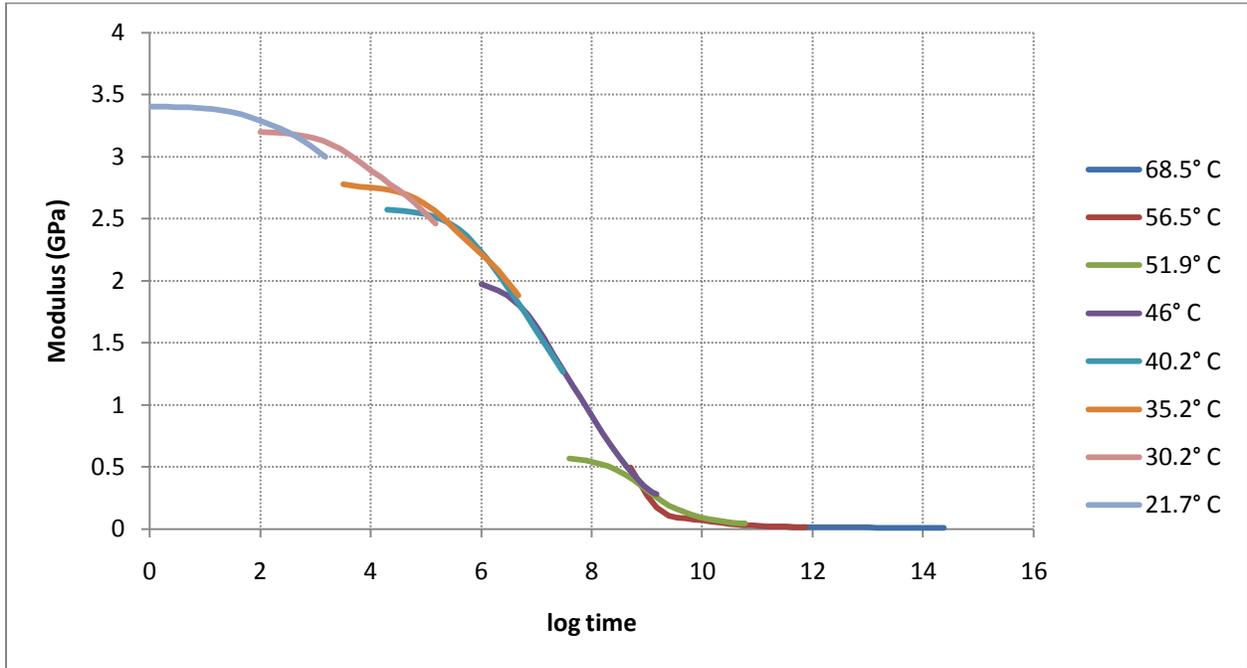


Figure 20: Shifted Relaxation Master Curve

This process is not entirely quantitative, and requires several iterations. The shape of the curve should be controlled to maintain a good shape, while also allowing for a good fit of the shift factors. The time-temperature shift factors ( $\alpha_T$ ) are then used to fit the WLF function (as described in the theoretical background) to provide an optimized, continuous function. The original shift values and WLF function are shown in Figure 21.

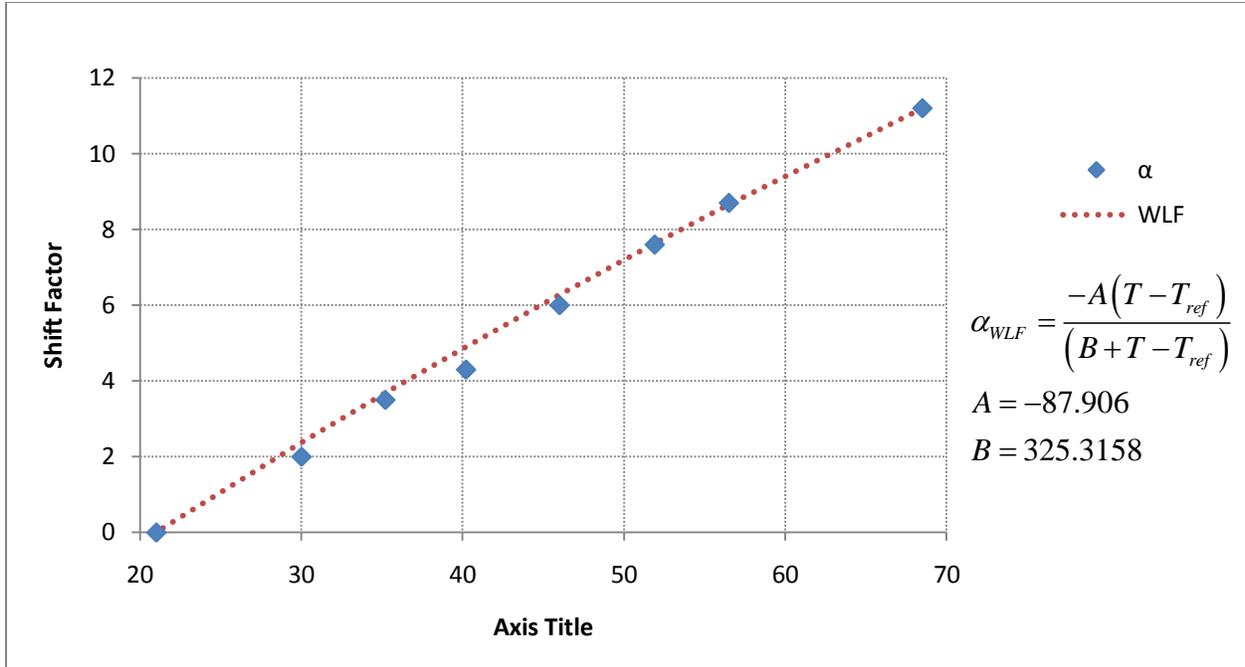


Figure 21: WLF Function and Shift Factors

The curves are then re-shifted using the optimized shift factors. By averaging overlapping relaxation curves, and approximates spaces in between, a continuous master curve of the average relaxation modulus values for all temperatures in the range of testing. The average values are then fitted to a nine term Prony series, as described in equation (10) and shown in Figure 22, which allows the approximated master curve to be used for modeling. The  $E_{\infty}$  term is the equilibrium modulus of the material, in this case 11.246 MPa, and

<b>E<sub>i</sub> (GPa)</b>	<b><math>\tau_i</math></b>
0.01098	5.0E+11
0.0544	4.0E+10
0.1469	7.0E+09
0.427	8.0E+08

0.7804	3.0E+08
0.8997	2.0E+07
0.4166	5.0E+05
0.441	23000
0.218	110

Table 3 shows the seven terms.

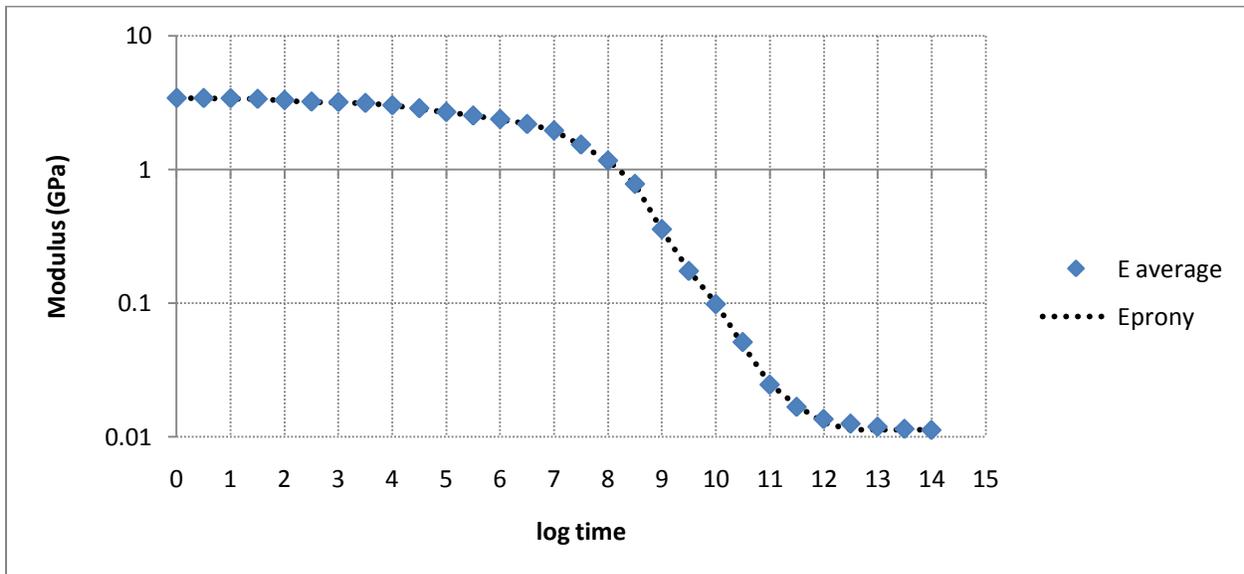


Figure 22: Prony Series and Averaged Master Curve

$E_i$ (GPa)	$\tau_i$
0.01098	5.0E+11
0.0544	4.0E+10
0.1469	7.0E+09
0.427	8.0E+08

0.7804	3.0E+08
0.8997	2.0E+07
0.4166	5.0E+05
0.441	23000
0.218	110

*Table 3: Prony Series Terms*

The Prony Series can then be used for modeling the given material.

## **Chapter 6: Conclusions and Future Work**

The FBG based measurement technique is proven to be effective in rapid evaluation of the visco-elastic properties of a common polymer material. The method was successfully implemented using a common polymer. The master curve of relaxation modulus was calculated and modeled using a Prony series.

This technique combined with the evolution property measurement technique could potentially yield all material properties of interest to packaging engineers, utilizing just two specimens. This results in a streamlined process which could be optimized to be routinely preformed by technicians, and fulfills a needed service by determining those properties. The proposed technique will provide a much-needed tool for rapid but accurate assessment of polymer properties, which, in turn, will enhance the accuracy of predictive modeling for design optimization of a microelectronics product at the conceptual stage of product development. In addition, the flexibility of the technique makes it suitable for a large range of polymeric materials. For simply visco-elastic measurement, the curing conditions (including heat generation effects) are inconsequential, as it only requires a specimen cured around an FBG. Depending on the range of measurement desired, and available resources for measurement, the proper configuration size can be determined.

For true implementation in industry, future work must be done to improve the testing method. Repeatability tests must be implemented to ensure that the results are consistent regardless of applied strain, or specimen size. Due to the rapid dropping of the weight, there is some initial oscillation of the specimen (and therefore BW and compliance data). Although the data is fitted when converting to relaxation modulus, it is always preferable to have more accurate raw data, and work should be done on the fixture to eliminate this effect as much as possible.

In addition, possible avenues for future work include modifying the testing fixture to be able to support larger weights, which would allow for more flexibility in specimen configuration and range of testing. The re-design of the fixture could also allow for the recovery period to be monitored; i.e. for the weight to be removed (or the hinge replaced) instantaneously. Some streamlining of the calculation process, perhaps a graphic user interface, is needed to be eligible for a thorough technology transfer, intending for the work to be completed routinely by technicians.

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